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A non-synchronous method of demodulating amplitude-modulated signals with asymmetrical sidebands

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RESEARCH DEPARTMENT

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SUMMARY

The theoretical requirements for demodulating a.m. signals with asymmetrical sidebands are outlined. A novel form of demodulator is described which makes use of the variation in the phase of the modulated carrier to derive a signal that can correct the output of a normal envelope detector for non-linear distortion. Several schematic arrangements are given together with the circuit used in an experimental demodulator. The limitations and advantages of the method are discussed and compared with those of a conventional synchronous demodulator.

1. INTRODUCTION

It is well known that the envelope of an amplitude-modulated carrier wave is not a faithful representation of the original modulating signal if the symmetry of the upper and lower sidebands is perturbed. In order to preserve envelope fidelity, it is necessary that the amplitudes of the upper and lower side-frequencies are equal and that their phases are precisely anti-symmetrical with respect to the carrier phase. Moreover, the carrier must at all times be of sufficient amplitude to prevent overmodulation. The output of a conventional envelope detector is therefore a distorted version of the original modulating signal whenever sideband asymmetry exists at the input to the detector. Furthermore, the kind of distortion introduced (sometimes called quadrature distortion) is non-linear so that harmonics and intermodulation products of the original signal spectrum appear as spurious components in the demodulated version. Sideband asymmetry at the input to the detector may arise due to propagation phenomena, mistuning in the receiver, or be deliberately introduced at the transmitter to conserve bandwidth as, for example, in a vestigial-sideband television transmission.

There are several methods of demodulating amplitude-modulated signals with asymmetrical sidebands which avoid the non-linear distortion assocaited with envelope detection. The most common of these, and certainly the most elegant and complete solution conceptually, is synchronous demodulation. This well-known method which is discussed in more detail later, relies on providing in the receiver a periodic signal which is in precise synchronism with the incoming carrier. This requirement is not easy to implement in many applications, e.g. a domestic m.f. radio receiver, without a substantial increase in cost. Another approach is to use an envelope detector and to apply to its output a correction which cancels the non-linear distortion components. Voelcker[1] has shown that for a single-sideband transmission the correction signal required can, under certain constraints, be derived entirely from the (distorted) output of an envelope detector. One constraint is that the carrier component is sufficiently strong so that overmodulation does not occur, and another is that the absolute carrier level at the input to the envelope detector is constant, which implies precise a.g.c. circuitry. The proposed new method,[2] which is the subject of this report, is similar in approach but the required correction signal is derived from the variation in the *phase* of the modulated carrier. The potential advantage of this approach, over classical synchronous demodulation, is that the need to provide a regenerated carrier in the receiver is removed, and this could lead to a cheaper and simpler form of demodulator. There are, however, important limitations of the method which arise due to phase ambiguity and these may restrict its general application.

2. THEORETICAL BASIS OF THE METHOD

The effect of sideband asymmetry on the carrier wave can be seen by comparing an example of single-sideband modulation (which is clearly an extreme form of sideband asymmetry) with that of a symmetrical double-sideband transmission. In the latter case, a single component of the modulating signal gives rise to a symmetrical pair of side-frequencies which in the conventional vector representation

of Fig. 1(a) are shown by a pair of counter-rotating vectors, BC and BD, with respect to the carrier component AB. The resultant BE of the side-frequencies is always in phase with the carrier so that AE represents the instantaneous amplitude of the carrier wave. Hence, from Fig. 1(a), an envelope detector would give an output $1+a\cos pt$, where $a\cos pt$ is the original modulation component and the carrier is of unit amplitude. Therefore, apart from a constant d.c. term, the envelope is an undistorted version of the original signal. Consider now Fig. 1(b) which shows a single-sideband arrangement having the same modulation depth. The spectrum now has a single side-frequency of amplitude a and angular frequency $(\omega_c + p)$ where ω_c is the carrier frequency. The vector representation for this case shows that the resultant, AF, is not always in phase with the carrier, the phase difference being a function of the amplitude and phase of the modulating signal. The instantaneous amplitude M of the carrier wave is not linearly related to the original modulation $a\cos pt$, as it was in the symmetrical double-sideband situation. However, it is easily seen from the vector geometry that the required output is in fact $M(t)\cos\phi(t)$, where the M and ϕ are written as functions of t to emphasize their time dependence.

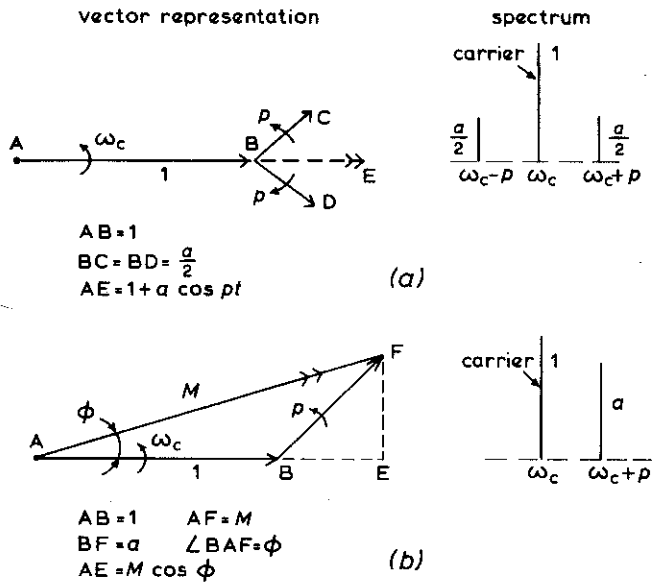

Fig. 1 - Representations of single-tone amplitude modulation:

(a) Double-sideband (sideband symmetry)

(b) Single-sideband (sideband asymmetry)

The above examples relate to single modulation components for simplicity, but it can be shown that a general expression for a modulated carrier-wave $E(t)$ is given by

$$E(t) = M(t)\cos[\omega_c t + \phi(t)] \qquad (1)$$

and that the correctly demodulated output (in the sense that it is free from non-linear distortion) is $M(t)\cos\phi(t)$. That this is correct is shown by considering the output from an ideal synchronous detector. Let the input to the synchronous detector be given by Equation (1), and this be multiplied in the detector by the regenerated carrier $2\cos\omega_c t$. The product is

$$2E(t)\cos\omega_c t = 2M(t)\cos\omega_c t.\cos[\omega_c t + \phi(t)]$$
$$= M(t)\left\{\cos\phi(t) + \cos[2\omega_c t + \phi(t)]\right\}$$

which, after passing the signal through a low-pass filter, leaves $M(t)\cos\phi(t)$ as the demodulated output. Thus the required undistorted output is obtained if the function $M(t)\cos\phi(t)$ can be accurately generated from the carrier-wave.

3. APPROXIMATE NON-SYNCHRONOUS METHODS

The $M(t)$ factor is easily obtained from the output of an envelope detector, but the $\cos\phi(t)$ factor is more difficult to obtain. The method suggested here is to extract the phase modulation component $\phi(t)$ from the incoming carrier wave and then synthesize the cosine function by approximate means. For example, one basic arrangement of the method is shown in Fig. 2(a). The output from an intermediate-frequency amplifier, $M(t)\cos[\omega_i t + \phi(t)]$, where ω_i is the intermediate frequency, is split into two paths. In one path the signal is passed through a symmetrical limiter to remove the amplitude modulation. The limiter output $\cos[\omega_i t + \phi(t)]$ is then fed to a frequency discriminator to obtain $\omega_i + \mathrm{d}/\mathrm{d}t\{\phi(t)\}$. The d.c. component is removed and the signal passed through an integrator to obtain a signal proportional to $\phi(t)$. The phase component is then squared and multiplied by the output from an envelope detector in the alternative path to obtain a correction signal $\beta M(t)\phi^2(t)$, where β is an arbitrary gain factor. Finally, the correction signal is subtracted from the output of the envelope detector to give $M(t) - \beta M(t)\phi^2(t)$ as the final output of the demodulator. Setting $\beta = ½$, the output is seen to be a first order approximation to the function $M(t)\cos\phi(t)$ for, by series expansion,

$$M(t)\cos\phi(t) = M(t)\left\{1 - \frac{\phi^2(t)}{2} + \frac{\phi^4(t)}{24} - \ldots\right\} \qquad (2)$$

For $\phi(t)$ equal to $\pi/2$ radians, the error in the correction signal due to the approximation is $(\pi^2/8) : 1$, which is 22% approximately. However, in practice, the value of β would be adjusted to spread the error more uniformly. For example, with $\beta = 1/2{\cdot}2$ the correction signal would be in error by not more than ±10% over the range $0 \leqslant |\phi(t)| \leqslant \pi/2$ which corresponds to the range of modulation depths 0 to 100%.

To illustrate the correction process, Fig. 3 shows the waveforms at the points A to F in Fig. 2(a) when the input signal comprises a carrier and a single side-frequency component (90% of the carrier amplitude).

Alternative circuit arrangements are shown in Figs. 2(b) and 2(c). In Fig. 2(b) the correction is effected before envelope detection. This may be advantageous if the envelope detector is imperfect, introducing its own distortions. In Fig. 2(c) a triple-input linear multiplier is used to form the product $M(t)\,(1-\phi(t)/\sqrt{2})\,(1+\phi(t)/\sqrt{2})$ which is equivalent to the output of the other arrangements.

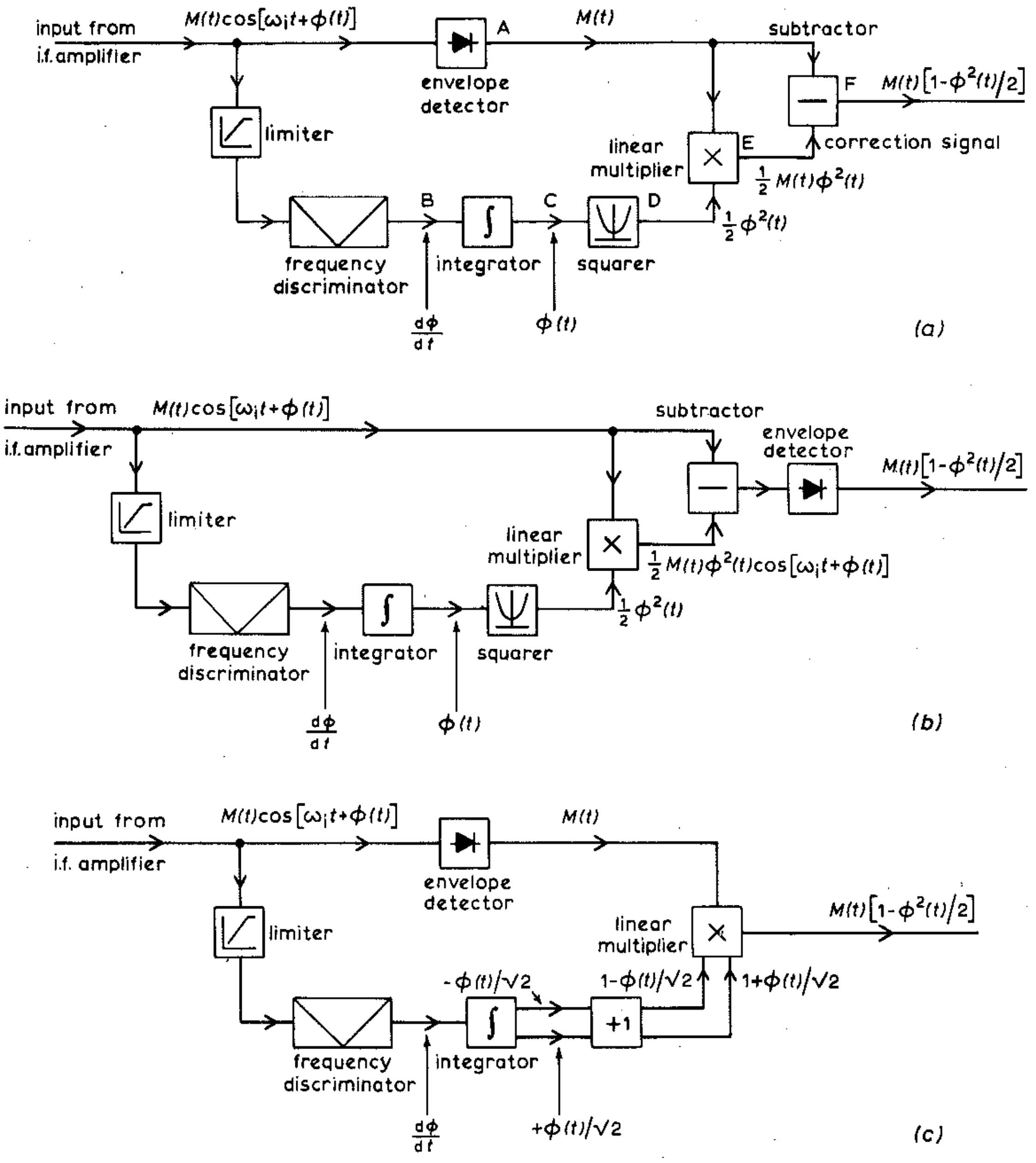

Fig. 2 - Non-synchronous detector arrangements

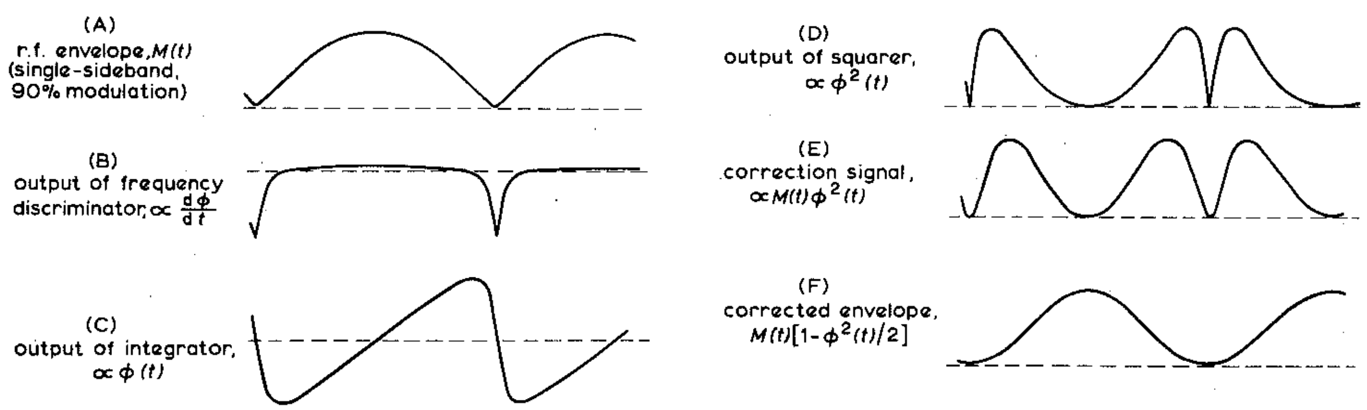

Fig. 3 - Waveforms at various points in detector chain (see Fig. 2(a)), for single-tone modulation and single-sideband transmission

4. LIMITATIONS

Apart from small errors due to the approximation to the cosine function, the performance of the non-synchronous demodulator described above is similar in every respect to that of a conventional synchronous demodulator except that it will not deal with overmodulation. The difficulty is that when the input signal runs into overmodulation there is a carrier-phase jump of π radians on entering and leaving the overmodulation excursion. This gives rise to a pulse at the output of the frequency discriminator which perturbs the correction signal and therefore the final output. The mechanism is similar to that which produces the well-known 'plops' in f.m. demodulators subjected to interference with a peak value exceeding the carrier amplitude. Fig. 4 illustrates the effect of overmodulation for the particular case of a single-sideband input signal comprising a carrier and one side-frequency which progressively increases in amplitude until it exceeds that of the carrier and then subsides. In Fig. 4 the voltage across the load at the output of the frequency discriminator is shown as a function of time. Until the side-frequency component exceeds that of the carrier the mean voltage per cycle of modulation is constant, its value corresponding to the carrier frequency. During the overmodulation period, however, the mean voltage (although still constant in this particular example) has a different value, in fact that corresponding to the side-frequency. In this manner, the ideal output from the discriminator becomes marred by the addition of a rectangular pulse whose height is proportional to the difference in frequency between the carrier and that of the side component, and whose width is proportional to the length of time during which the amplitude of the side component exceeds that of the carrier. In the single-sideband transmission of a complex modulating signal, having a band of side-frequencies, the added pulse during the overmodulation period will, of course, be of irregular shape and its average height will depend on the mean frequency of the sideband components. The pulse does not occur during overmodulation in a double-sideband transmission which has sideband symmetry because the mean frequency of the sideband components is always that of the carrier.

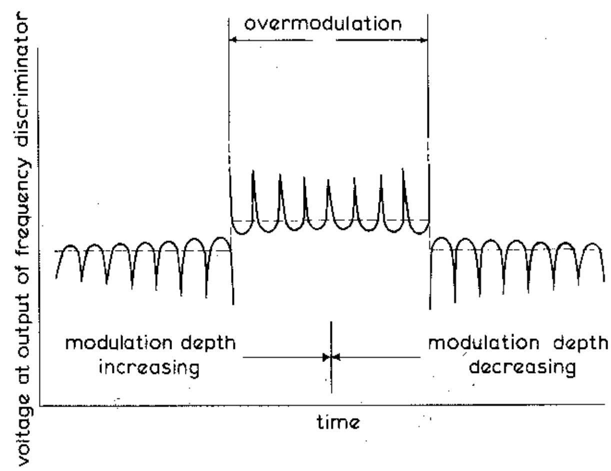

Fig. 4 - The effect of overmodulation on the frequency-discriminator output

Another limitation of the non-synchronous method described is that it is difficult to implement an integrator which performs well at very low frequencies with the result that the envelope distortion is less effectively corrected for these components.

Symmetrical limiting is somewhat difficult to achieve if the intermediate frequency is high, although in the demodulator described it should be remembered that phase errors which occur due to the limiter deficiencies affect only the correction signal.

Linear multiplication presents no problem with the advent of stable integrated circuits.

5. EXPERIMENTAL DEMODULATOR

An experimental demodulator was constructed to demonstrate the principle of the asynchronous method and help to assess the feasibility of this approach. Fig. 5 shows the circuit used, which is based largely on the schematic arrangement shown in Fig. 2(*c*). It was built-up mainly from general-purpose integrated circuits. Briefly, limiting and frequency discrimination are achieved by one integrated circuit (PA.189) and an external tuned circuit adjusted to resonate in the region of 1 MHz. The filtered output from the discriminator is d.c. coupled to a single p.n.p. transistor stage with capacative (collector-to-base) feedback which forms the integrator. The four-quadrant linear-multiplier follows closely the design proposed by Gilbert[3] in which if two bipolar-signals X and Y, say, form the inputs, the collector current in one of the output pair of transistors is proportional to $(1-XY)\,I_E$, where I_E is the common emitter current. Hence if we arrange that $X = Y = \phi(t)/\sqrt{2}$ and also that I_E is proportional to $M(t)$ we obtain the required output current, namely $M(t)\ (1-\phi(t)^2/2)$. In fact, the transistor (T in Fig. 5) in the emitter circuit was biased both to perform envelope detection and to provide a third input feed to the multiplier, the rectified carrier components being filtered-off at the final output.

A diode chain was used to provide the bias feeds to the multiplier transistors. It was found that the integrator began to deteriorate in performance below about 300 Hz.

The demodulator was tested by injecting either single or double-sideband modulated carriers at 1 MHz by direct feed from low-power modulators. The circuit parameters were adjusted to obtain optimum correction of single-sideband distortion using an audio-tone generator as the modulating source. Sound programmes (both music and speech) were also used for brief listening tests, and it could be demonstrated that reproduction when using the non-synchronous demodulator was almost indistinguishable between single-sideband and double-sideband inputs. The impulse-type noise arising from overmodulation peaks, which can arise if the maximum modulation depth is not strictly limited to less than 100%, was found to be subjectively disturbing.

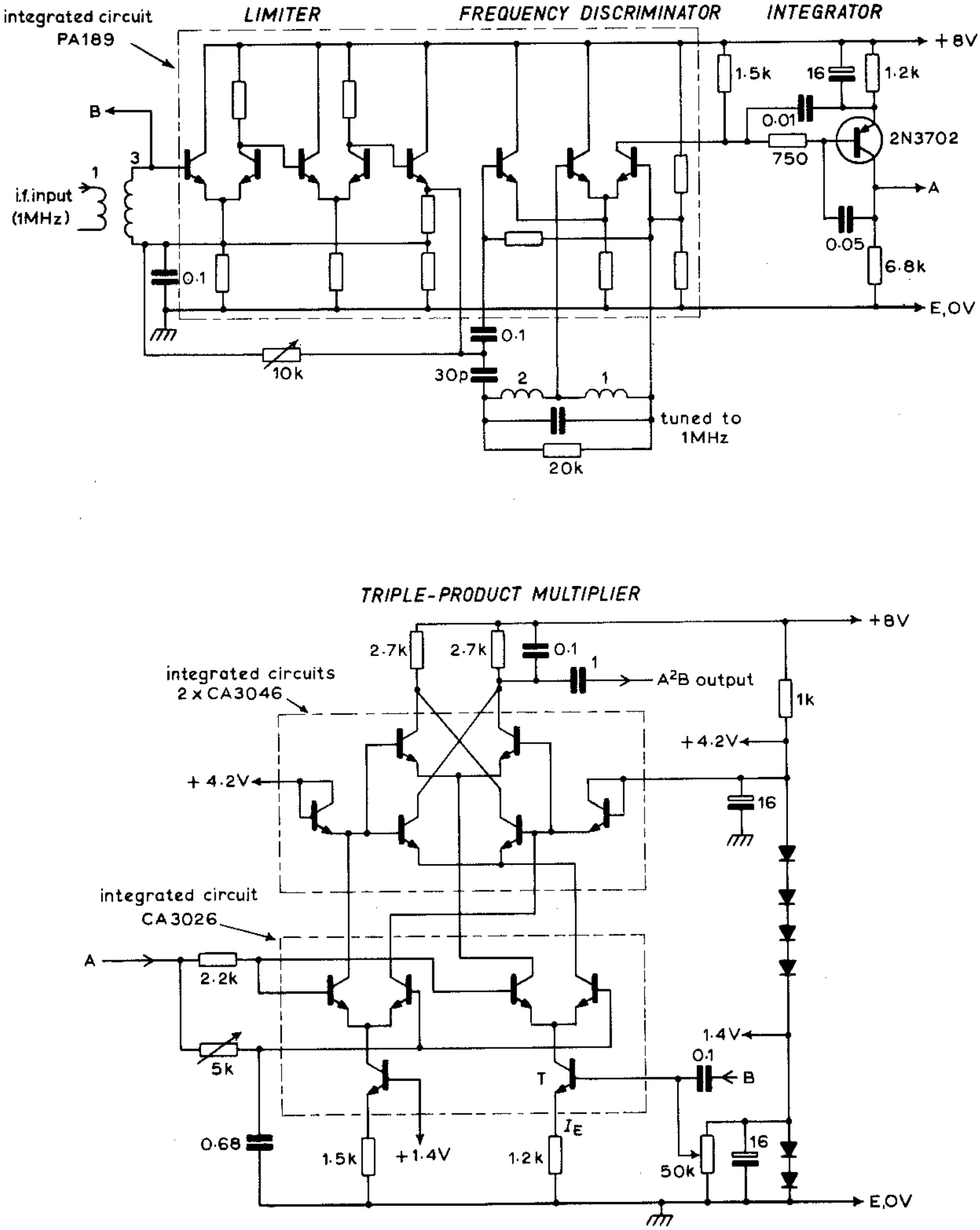

Fig. 5 - Experimental non-synchronous demodulator

The intrinsic advantage of the non-synchronous method, over the synchronous approach, is its insensitivity to the frequency of the carrier. In the experimental demodulator the carrier frequency could be varied by at least ±2 kHz without significant change in the demodulated output.

6. POSSIBLE APPLICATIONS

The new demodulator can be regarded as an improved form of envelope detector because it will substantially eliminate non-linear distortion due to sideband asymmetry.

The restricted range of modulation depths (i.e. not exceeding 100%) is also similar to that of a conventional envelope detector except that the limitation on overmodulation is more abruptly defined due to the effects of carrier-phase jumping. Hence the new demodulator could, in theory, be employed to advantage for any communication application which uses a conventional envelope detector in the receiver, providing the transmissions are not likely to significantly violate the modulation-depth limitation when the r.f. signal spectrum is simultaneously asymmetrical.

Consider the potential advantages, for example, if the proposed demodulator were incorporated in a standard transistor portable for m.f. reception of normal double-sideband transmissions. The selectivity of the r.f. plus i.f. circuits of these receivers is typically that shown in Fig. 6(*a*). It is clear that there is little room for mistuning before sideband asymmetry causes distortion. Fig. 6(*c*) shows the effect on the amplitude symmetry of a nominal, d.s.b. transmission spectrum when the receiver is mistuned by 3 kHz. Not only is the carrier amplitude reduced (by about 4 dB), but the spectrum is severely asymmetrical and, followed by a conventional envelope detector, would probably result in objectionable non-linear distortion. Using the new demodulator this distortion would not arise, so that the receiver would have in effect a substantially greater acceptable tuning range. Moreover, advantage could be taken of this when there is interference from an adjacent channel because one is able to tune away from the interfering station. In the example shown in Fig. 6, approximately 10 dB greater rejection of the adjacent-channel interference would be obtained by the 3 kHz mistuning.

Colour television is another possible field of application. Here saturation errors arise due to quadrature distortion when conventional envelope detection is used. The problem becomes more serious for rebroadcast transmissions because the quadrature distortion occurs at least twice, once in each rebroadcast receiver (there may be two or more rebroadcast links in tandem) and again in the domestic receiver. Synchronous detection is the ideal solution but this requires considerable circuit complexity. Moreover it may fail if the carrier frequency is out of tolerance. The proposed demodulator does not involve expensive components and may be a useful alternative approach. For this application, the video frequencies most in need of correction are centred around the chrominance subcarrier; this eases the design of the integrator in the demodulator. Nevertheless, it may be advantageous to correct over a wider range of video frequencies in order to reduce quadrature distortion associated with luminance detail.

In principle, the demodulator should aid the reception of a.m. transmissions which are subject to selective fading, since any sideband asymmetry introduced will not lead to non-linear distortion, provided that sufficient carrier is maintained at the input to the demodulator to prevent overmodulation.

7. RECOMMENDATIONS FOR FUTURE WORK

In order to assess the feasibility of the method more fully, it is suggested that experimental versions of the demodulator be incorporated in both an a.m. radio receiver and a colour television monitor (or receiver). In the radio application the effects of noise and interference etc. could be determined realistically. In the television application, further development of the demodulator circuitry would be necessary to deal with the higher intermediate frequency. Implementation would, in fact, have been somewhat difficult with components available hitherto, but progress in integrated circuits should make development easier. Consideration should also be given to the possibility of using the proposed demodulator for h.f. re-broadcast receptions of d.s.b. transmissions at overseas transmitters. It could have practical advantages over a synchronous detector, but it would probably require enhancement of the carrier by i.f. selectivity (the resulting loss of high-frequency response being corrected at a.f.) so as to reduce the frequency of occurrence of overmodulation due to selective fading of the carrier.*

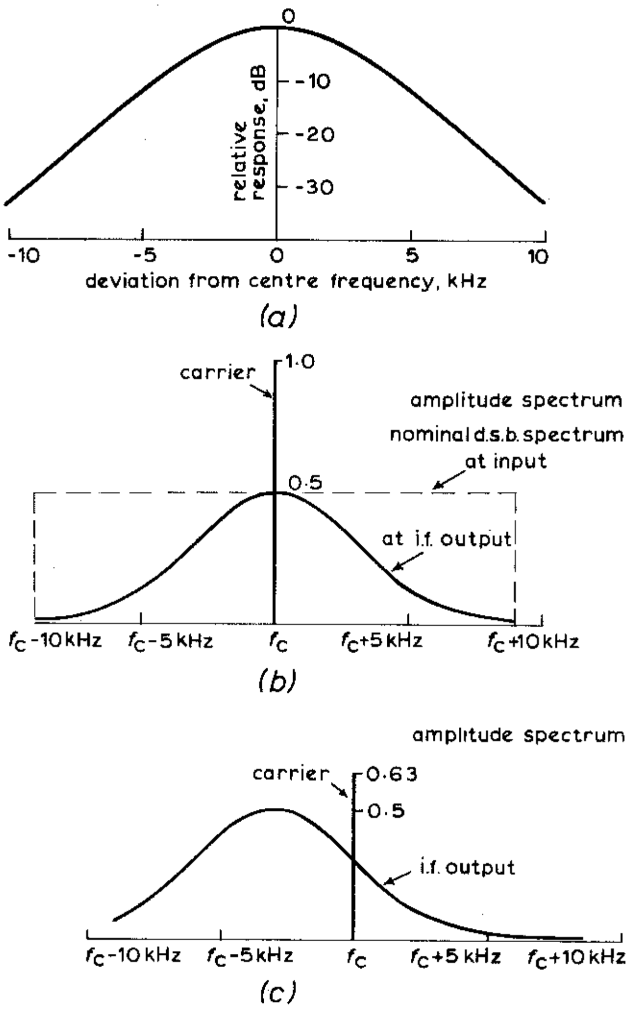

Fig. 6 - Illustrating sideband asymmetry due to mistuning in a typical m.f. receiver

(*a*) r.f./i.f. selectivity characteristic of receiver

(*b*) Spectrum of d.s.b. signal at i.f. output when correctly tuned

(*c*) Spectrum of d.s.b. signal at i.f. output due to mistuning by 3 kHz.

* Suggested by Dr. G.J. Phillips.

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